

Size estimation of *Synbranchus marmoratus* and *Synbranchus madeirae* (Teleostei) based on isolated cranial and post-cranial bones

by

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Abstract. – The remains of South American swamp-eels are commonly recovered in pre-Columbian archaeological sites and swamp-eels are an important prey of piscivorous predators. In an attempt to assess the size classes of modern and archaeological fish from Bolivia, here we provide allometric regression equations for *Synbranchus marmoratus* and *S. madeirae*, resulting in total body length estimations on the basis of isolated skeletal elements. A total of 68 modern skeletons for *Synbranchus marmoratus* and 82 for *Synbranchus madeirae* were analysed. Measurements were taken on cranial (dentary, ectopterygoid, neurocranium, articular, hyomandibular, cleithrum) and post-cranial bones (first and second precaudal vertebrae). Our study shows that bone elements are highly correlated with total body lengths, which allows for a reliable reconstitution of *Synbranchus* size for paleontological, archaeological and dietary studies.

Résumé. – Estimation de la taille de *Synbranchus marmoratus* et *Synbranchus madeirae* (Teleostei) sur la base d'os crâniens et post-crâniens isolés.

Les ossements d'anguilles des marais d'Amérique du Sud sont communément récupérés dans des sites archéologiques précolombiens et parmi les contenus stomacaux de prédateurs piscivores. Dans le but d'évaluer les classes de taille des populations de poissons modernes et archéologiques de Bolivie, nous fournissons ici des équations de régression allométrique pour *Synbranchus marmoratus* et *S. madeirae*, permettant d'obtenir des estimations de la longueur corporelle totale des individus sur la base d'éléments squelettiques isolés. Au total, 68 squelettes modernes pour la première espèce et 82 pour la seconde ont été étudiés. Des mesures ont été effectuées sur des os crâniens (dentaires, ectoptérygoïdes, neurocrânes, articulaires, hyomandibulaires, cleithrum) et post-crâniens (première et deuxième vertèbres précaudales). Notre étude montre que les éléments osseux sont fortement corrélés à la longueur totale du corps, ce qui permet une reconstitution fiable de la taille des *Synbranchus* pour les études paléontologiques, archéologiques et de régimes alimentaires.

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Recently, pre-Hispanic fisheries have attracted the attention of many scholars working in different parts of the Amazon region, such as the mouth of the Marajo Island, the Venezuelan Llanos and the Bolivian Llanos de Mojos. Nevertheless, little is known about the communities of fish inhabiting these systems, their diversity and the fish sizes (Garson, 1980; Erickson, 2000; Schaen, 2008). In former fisheries, the reconstruction of total body weight led to estimations of the contribution of specific taxa to the diet of ancient populations (Reitz *et al.*, 1987). The identification of specific size classes can be indicative of fishing based on prey size, the exploitation of precise aquatic spots (nurseries *versus* river bed) and the use of specialised techniques and tools. Furthermore, in the long term, a global decrease in the size of fish may indicate the overexploitation of specific taxa. In

addition to archaeological applications, estimating prey size allows us to access the predator diet and the ecological cycle, as fish are common prey for otters, birds and other piscivorous fishes (Hansel *et al.*, 1988).

Size estimations (length or weight) are based on the principle of allometry. As an organism matures, its calcified structures increase proportionally to its individual growth. However, not all the elements of the skeleton grow at the same rate. Thus, length and weight estimations are based on regression equations that allow us to reconstruct the allometry between isolated anatomical elements (bones, otoliths or scales) and the total body size of individuals. These equations can be obtained by taking a series of measurements on the skeletal elements of modern individuals (from juveniles to older specimens), of known length and weight.

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The relationship between bones and body sizes of modern specimens is described by the power function $Y = aX^b$, where “Y” is the unknown estimated total length (or weight), “X” is the bone measurement, “a” is the condition factor and “b” is the allometric coefficient (Teissier, 1948; Casteel, 1974; Reitz *et al.*, 1987).

Despite the fact that pioneering works on fish osteometry date back to the 1970s, most of the studies conducted so far have focused on European and North American species (*e.g.* Desse, 1984; Desse and Desse-Berset, 1996; Reitz *et al.*, 1987), and very few studies have been undertaken on South American freshwater fish. To date, some size estimation models exist for catfish (*Pterodoras granulosus*, *Hemiancistrus fuliginosus*, *Pogonopoma obscurum*, *Hypostomus* spp.), cichlids (*Crenicichla* spp., *Satanoperca pappaterra*, *Chaetobranchius flavescens*, *Astronotus crassipinnis*) and characids (*Hoplias malabaricus*, *Serrasalmus rhombeus*, *Pygocentrus nattereri*) (Ricken and Malabarba, 2009; Mallea-Cardenas and Becerra-Cardona, 2012; Loponte *et al.*, 2012; Becerra-Cardona *et al.*, 2015). However, with the exception of the tiger-fish (*Hoplias malabaricus*), these models are based on a limited number of cranial bone elements (premaxilla, pectoral spines), and do not concern post-cranial bones.

Synbranchids present a cylindrical eel-like body with no pectoral fins. Their average length is 50 cm but the largest individuals can reach up to ca. 150 cm. To date, there are two recognized species in the Amazon Basin: *Synbranchus marmoratus*¹ Bloch, 1795 and *Synbranchus madeirae* Rosen & Rumney, 1972. The first has a wide distributional area, including inland and estuarine areas from southern Mexico to Argentina, whereas the second seems to be restricted to the upper part of the Rio Madeira system (Rosen and Rumney, 1972). A third species, *Synbranchus lampreia* Favorito, Zanata & Assumpção, 2005, is confined to Marajó Island.

Zooarchaeological studies have revealed that swamp-eels were an important resource for pre-Columbian populations in Central and South America and one of the main taxa in settlements located in south-western Amazonian savannas (Béarez and Prümers, 2005; Von den Driesch and Hutterer, 2012; Prestes-Carneiro and Béarez, 2017). As synbranchid remains (*S. marmoratus* and *S. madeirae*) are frequently recovered from archaeological faunal assemblages, here we present regression equations allowing for the estimation of body length based on their isolated skeletal elements. In addition to archaeological applications, body size estimation can also be a useful tool for future ecological studies, as synbranchids are frequent prey of predatory birds.

¹ The species present in Bolivia is probably distinct from *S. marmoratus* but due to pending taxonomic clarification we prefer to consider it as it is generally recognized in ichthyological works in the area.

MATERIAL AND METHODS

The modern reference collection is made up of 68 skeletons of *Synbranchus marmoratus* and 82 skeletons of *S. madeirae*. The individuals were captured monthly from July 2015 to July 2016 in artificial ponds near San Pedro Nuevo (ca. 30 km north of Trinidad, Bolivia). The date of capture, preanal length (PAL), total length (TL), and weight were recorded. In order to obtain the most variability in terms of class size, we attempted to sample individuals with a TL ranging from 200 to 1080 mm TL. Skeleton preparation was carried out at the *Centro de Investigaciones de Recursos Acuáticos*, Trinidad and all the measurements were taken at the laboratory *Archéozoologie, Archéobotanique : sociétés, pratiques et environnements* of the *Muséum national d'Histoire naturelle*, Paris.

Due to the fact that the taxonomic identification of fish remains is generally undertaken on cranial remains, and that these are robust elements with higher chances of being preserved in archaeological assemblages, the majority of the bones selected in the present study are cranial bones (dentary, ectopterygoid, neurocranium, articular, hyomandibular, cleithrum), whilst two are post-cranial elements (second and third precaudal vertebrae).

The measurements were inspired by and adapted from general osteometry manuals, such as Morales and Rosenlund (1979), and the study carried out on eel-like fishes by Thieren *et al.* (2012). Names, descriptions and figures are presented in table I and figure 1. Each measurement was taken on the left sided element, from the smallest to the largest individual. For the bones with teeth (dentary, ectopterygoid), only the bones were measured, and not the teeth. The set of measurements were plotted in relation to the total length of individuals (in mm). The regression equation was then obtained using the power law, which provides the best prediction for allometric growth (Reitz *et al.*, 1987; Leach *et al.*, 1996; Thieren *et al.*, 2012). The accuracy of the equations was evaluated by the coefficient of determination (r^2) and the standard error of estimate (SEE).

RESULTS

The dentaries of these two species have some distinctive osteological features (Fig. 2): *Synbranchus madeirae* has a more slender and elongated dentary compared to *S. marmoratus*. The coronoid process and the symphyseal margin are also lower and thinner in *S. madeirae*. In the medial view, the tooth plate in *S. madeirae* is straight with 1 or 2 rows of teeth, and in *S. marmoratus* the tooth plate is curved and with 2 to 10 rows of teeth.

Ectopterygoids are especially well developed in synbranchids and bear teeth. The most notable differences

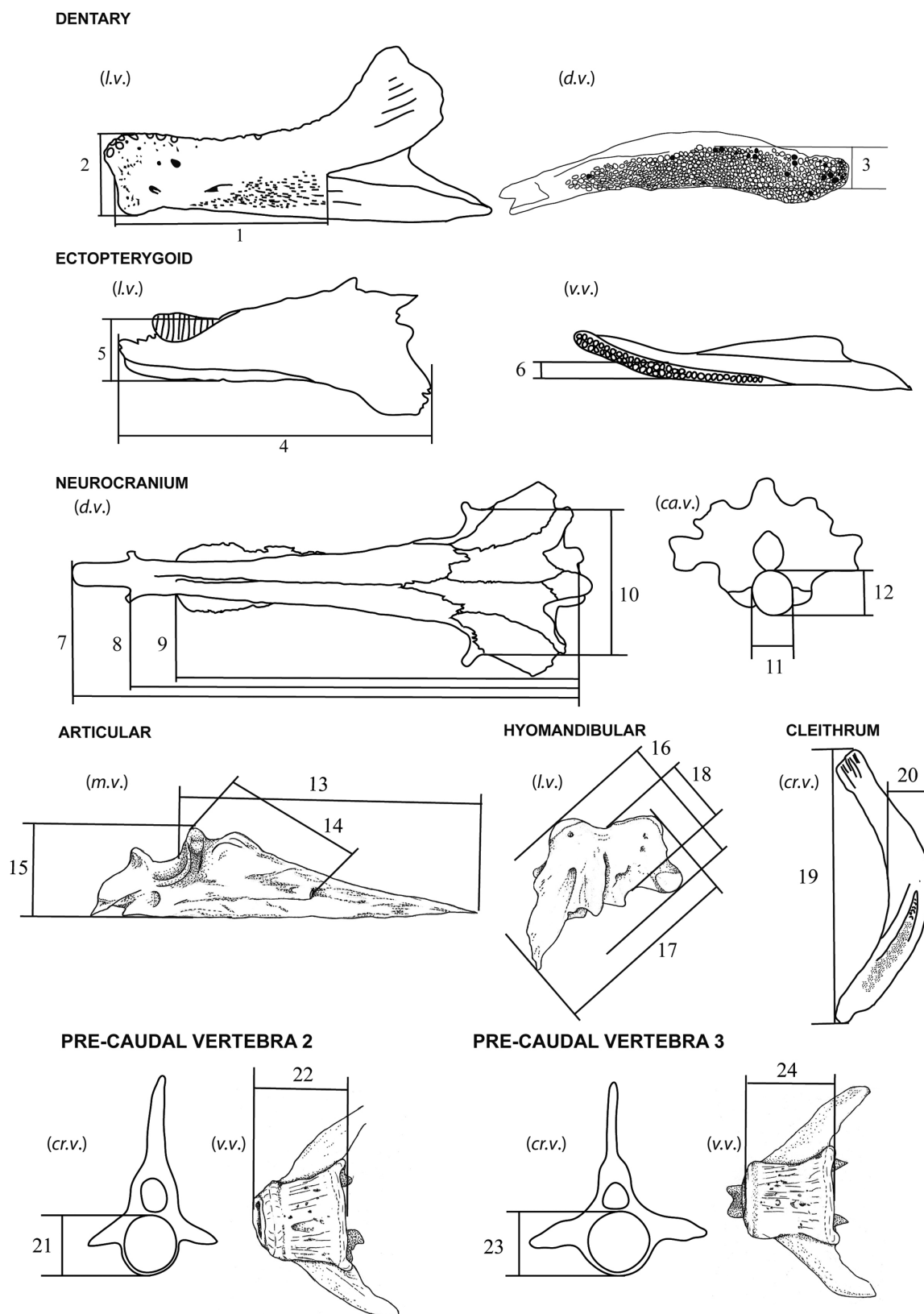
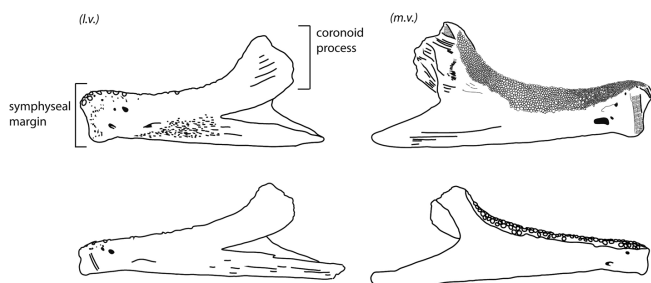


Figure 1. – *Synbranchus marmoratus* bones with measurements described in table I. Abbreviations: l.v. lateral view, m.v. medial view, d.v. dorsal view, v.v. ventral view, ca.v. caudal view, cr.v. cranial view.

Table I. – Measurements taken on each bone and illustrated in figure 1.

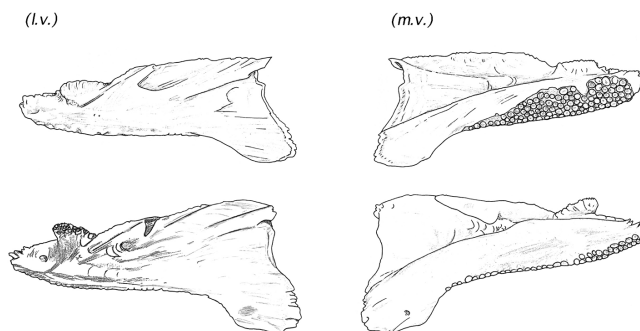
Anatomical element	Measurement number	Measurement description
Dentary	M ₁	Length of the dentary, from the most anterior part to the postero-lateral incisure
	M ₂	Anterior height of the dentary
	M ₃	Thickness of the tooth plate
Ectopterygoid	M ₄	Greatest length of the ectopterygoid
	M ₅	Ectopterygoid height, from the symphysis to the tooth plate
	M ₆	Thickness of the tooth plate
Neurocranium	M ₇	Total neurocranium length taken from the posterior part of the basioccipital to the most anterior part of the mesethmoid
	M ₈	Length from the posterior part of the basioccipital to the lateral ethmoid process
	M ₉	Length from the posterior part of the basioccipital to the most anterior part of the frontal
	M ₁₀	Neurocranium medio-lateral width taken at the sphenotic notch level
	M ₁₁	Width of the articular facet of the basioccipital
	M ₁₂	Height of the articular facet of the basioccipital
Articular	M ₁₃	Length from the articular facet to the anterior-most part of the articular
	M ₁₄	Length from the articular facet to the Meckel cartilage insertion
	M ₁₅	Greatest articular height
Hyomandibular	M ₁₆	Hyomandibular width
	M ₁₇	Hyomandibular greatest height
	M ₁₈	Hyomandibular width between the two median notches
Cleithrum	M ₁₉	Chord length of the cleithrum
	M ₂₀	Median width of the cleithrum
Precaudal vertebra 2 (PC2)	M ₂₁	Anterior height of PC2 centrum
	M ₂₂	Length of PC2 centrum
Precaudal vertebra 3 (PC3)	M ₂₃	Anterior height of PC3 centrum
	M ₂₄	Length of PC3 centrum

Figure 2. – Lateral (l.v.) and medial (m.v.) views of *Synbranchus marmoratus* (upper drawings) and *S. madeirae* (lower drawings) left dentaries.

between *S. marmoratus* and *S. madeirae* are the shape of the articulation with the frontal and the number of rows of teeth (Fig. 3).

The total lengths of *S. marmoratus* ranged between 235 mm and 835 mm and those of *S. madeirae* range between 225 mm and 1080 mm. Samples are representative for different sizes and weights in both species, i.e. there is significant variability among samples, which can be observed by the high standard deviation values (Tabs II, III; Fig. 4).

As some skeletal elements disintegrated during the osteological preparation, the number of measured specimens is

Figure 3. – Lateral (l.v.) and medial (m.v.) views of *Synbranchus marmoratus* (upper drawings) and *S. madeirae* (lower drawings) left ectopterygoids.

sometimes lower than the total number of individuals, therefore, N is given for each measurement. This is the case for the neurocranium, which is not ossified in juveniles smaller than 320 mm TL. Regression equations estimating the total lengths of *S. marmoratus* and *S. madeirae* were highly significant (Tabs IV, V). Most determination coefficients (r^2) range between 0.82 and 0.96, indicating that there is a significant correlation between bony elements and the size and weight of specimens.

Table II. – Biometric information concerning *Synbranchus marmoratus* specimens (N = 68). S.D.: Standard deviation.

	Min.	Max.	Mean	S. D.
Total length (mm)	235	835	397.85	118.17
Prealanal length (mm)	162	620	285.15	87.41
Weight (g)	14	991	111.34	157.25

Table III. – Biometric information concerning *Synbranchus madeirae* specimens (N = 82). S.D.: Standard deviation.

	Min.	Max.	Mean	S. D.
Total length (mm)	225	1080	330.91	105.76
Prealanal length (mm)	143	750	483.18	143.30
Weight (g)	10	1657	157.05	99.42

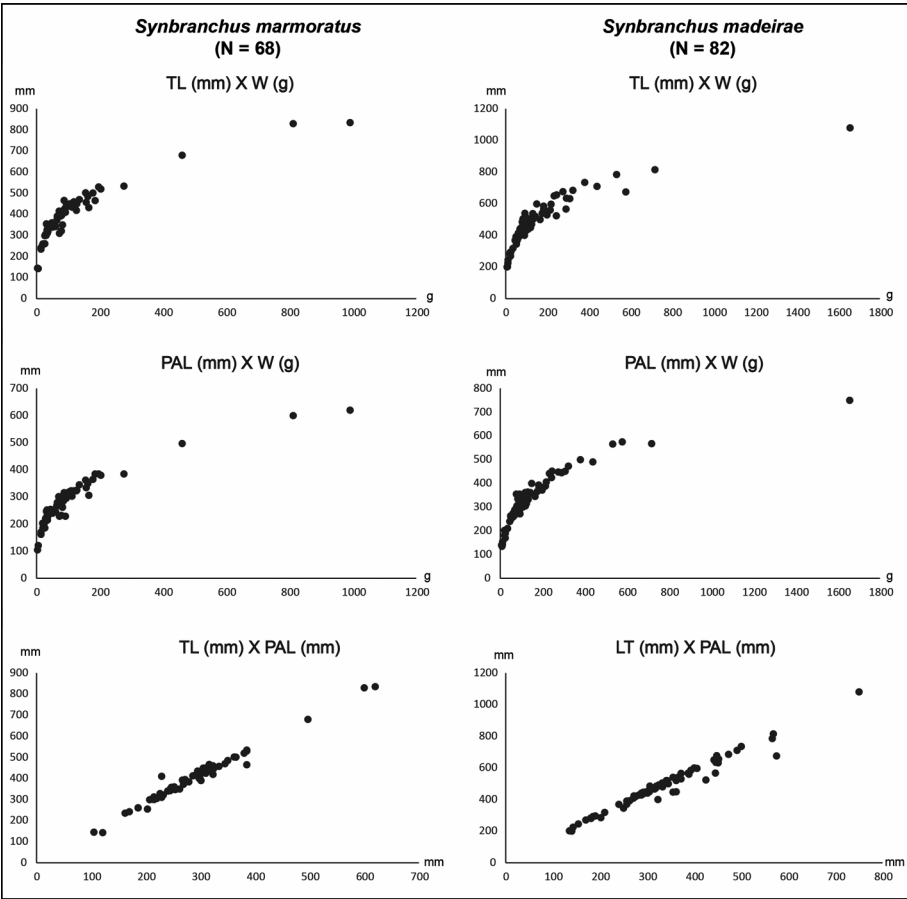


Figure 4. – Scatter plots of *S. marmoratus* and *S. madeirae*. Total length (TL), Prealanal length (PAL) and weight (W).

The standard error of estimate (SEE) indicated the error in prediction, which is a useful tool for evaluating the accuracy of the size reconstruction. Contrasting SEE values showed that some bones are better size predictors than others. In *S. marmoratus*, the majority of the bony elements presented SEE values oscillating around 20, except for tooth plate thickness, which is a measurement that seems to vary according to individuals. SEE values obtained for *S. marmoratus* are higher than those obtained for *S. madeirae*.

DISCUSSION AND CONCLUSIONS

Here we present regression equations allowing us to estimate the total lengths of *S. marmoratus* and *S. madeirae*. Slight differences in determination coefficients indicate

that some measurements are more appropriate than others; the highest values were obtained for the neurocranium total length (M_7). Lower r^2 values were observed for the thickness of the tooth plate (M_6) in both species. This result might be related to the variability in form and thickness of the tooth plate in *S. marmoratus*. In this respect, Günther (1870: 16), who was one of the first scholars noting this variability, quoted “The varieties of this widely distributed species are numerous, especially with regard to the width of the snout and head, form of the gill-opening, *width of the palatine band of teeth*, and coloration”. This variation in the shape and form of bony elements integrating the mouth of synbranchids certainly influenced the accuracy of size predictions and should thus be further investigated.

Comparing the accuracy of the predictions obtained for cranial elements in relation to vertebrae, we observe that

Table IV. – Regression equations obtained for *Synbranchus marmoratus* total length estimation where “N” corresponds to the number of measured specimens, “r²” corresponds to the determination coefficient and “SEE” corresponds to the standard error of estimate.

	Measurement	N	Equation	r ²	SEE
Dentary	M ₁	61	TL = 72.168*(M ₁) ^{0.7515}	0.9434	26.48
	M ₂	61	TL = 223.75*(M ₂) ^{0.6188}	0.9356	28.61
	M ₃	61	TL = 0.0001*(M ₃) ^{1.5893}	0.8835	47.01
Ectopterygoid	M ₄	60	TL = 55.218*(M ₄) ^{0.738}	0.9344	23.03
	M ₅	60	TL = 187.38*(M ₅) ^{0.7493}	0.9196	29.70
	M ₆	60	TL = 344.08*(M ₆) ^{0.4557}	0.8503	47.32
Neurocranium	M ₇	47	TL = 24.995*(M ₇) ^{0.8118}	0.9651	20.81
	M ₈	56	TL = 31.308*(M ₈) ^{0.785}	0.9594	21.42
	M ₉	56	TL = 40.963*(M ₉) ^{0.7527}	0.9623	21.32
	M ₁₀	55	TL = 55.224*(M ₁₀) ^{0.9002}	0.9455	25.06
	M ₁₁	56	TL = 202.37*(M ₁₁) ^{0.7367}	0.9427	25.72
	M ₁₂	56	TL = 186.58*(M ₁₂) ^{0.8346}	0.9583	21.93
Articular	M ₁₃	54	TL = 72.027*(M ₁₃) ^{0.7416}	0.9588	23.52
	M ₁₄	54	TL = 120.25*(M ₁₄) ^{0.7723}	0.9452	29.48
	M ₁₅	54	TL = 193.23*(M ₁₅) ^{0.6853}	0.9416	28.87
Hyomandibular	M ₁₆	48	TL = 115.15*(M ₁₆) ^{0.7867}	0.9237	28.68
	M ₁₇	49	TL = 115.15*(M ₁₇) ^{0.7867}	0.9237	29.51
	M ₁₈	49	TL = 206.05*(M ₁₈) ^{0.7316}	0.9314	31.75
Cleithrum	M ₁₉	57	TL = 43.916*(M ₁₉) ^{0.7841}	0.9445	24.21
	M ₂₀	57	TL = 251.99*(M ₂₀) ^{0.7228}	0.9174	32.19
PC2	M ₂₁	19	TL = 191.83*(M ₂₁) ^{0.8112}	0.9642	39.01
	M ₂₂	19	TL = 128.13*(M ₂₂) ^{1.0403}	0.9591	30.08
PC3	M ₂₃	19	TL = 194.77*(M ₂₃) ^{0.7931}	0.9657	37.72
	M ₂₄	19	TL = 120.59*(M ₂₄) ^{0.9987}	0.9676	22.10

Table V. – Regression equations obtained for *Synbranchus madeirae* total length estimation where “N” corresponds to the number of measured specimens, “r²” corresponds to the determination coefficient and “SEE” corresponds to the standard error of estimate.

	Measurement	N	Equation	r ²	SEE
Dentary	M ₁	81	TL = 65.783*(M ₁) ^{0.8053}	0.9152	47.05
	M ₂	81	TL = 261.42*(M ₂) ^{0.7575}	0.8785	49.95
	M ₃	81	TL = 589.12*(M ₃) ^{0.6233}	0.6467	81.90
Ectopterygoid	M ₄	80	TL = 48.92*(M ₄) ^{0.8032}	0.9365	39.99
	M ₅	80	TL = 186.37*(M ₅) ^{0.8096}	0.9112	41.57
	M ₆	80	TL = 528.86*(M ₆) ^{0.6621}	0.8254	61.17
Neurocranium	M ₇	41	TL = 20.41*(M ₇) ^{0.8963}	0.9442	35.25
	M ₈	66	TL = 25.456*(M ₈) ^{0.8702}	0.9408	31.85
	M ₉	72	TL = 34.663*(M ₉) ^{0.8257}	0.9563	29.95
	M ₁₀	72	TL = 59.474*(M ₁₀) ^{0.8812}	0.948	35.37
	M ₁₁	72	TL = 224.95*(M ₁₁) ^{0.716}	0.9382	34.85
	M ₁₂	72	TL = 215.93*(M ₁₂) ^{0.8127}	0.9525	29.44
Articular	M ₁₃	81	TL = 61.431*(M ₁₃) ^{0.8173}	0.9241	42.80
	M ₁₄	81	TL = 131.74*(M ₁₄) ^{0.7768}	0.9185	46.52
	M ₁₅	81	TL = 201.21*(M ₁₅) ^{0.7549}	0.9281	42.92
Hyomandibular	M ₁₆	73	TL = 100.98*(M ₁₆) ^{0.9}	0.919	48.50
	M ₁₇	73	TL = 76.095*(M ₁₇) ^{0.9246}	0.9247	44.47
	M ₁₈	73	TL = 224.51*(M ₁₈) ^{0.7882}	0.9151	46.96
Cleithrum	M ₁₉	73	TL = 42.79*(M ₁₉) ^{0.8108}	0.9322	40.56
	M ₂₀	73	TL = 246.31*(M ₂₀) ^{0.7079}	0.9203	40.43
PC2	M ₂₁	23	TL = 237.53*(M ₂₁) ^{0.7035}	0.9312	52.24
	M ₂₂	23	TL = 164.79*(M ₂₂) ^{0.9462}	0.9157	55.80
PC3	M ₂₃	23	TL = 249.21*(M ₂₃) ^{0.6758}	0.9323	51.24
	M ₂₄	23	TL = 179.4*(M ₂₄) ^{0.8171}	0.9404	63.43

there are no significant differences in determination coefficients and SEE between these elements. This result contrasts with what is observed for the European eel, *Anguilla anguilla* (Linnaeus, 1758), where vertebrae seem to be more reliable size predictors than cranial elements (Thieren *et al.*, 2012).

As fish are one of the most exploited and widespread food resources recovered from pre-Columbian settlements in the Amazon Basin, osteometry can be a valuable tool for archaeologists to estimate the length of former fish individuals using isolated bones. Size estimations attempt to better understand the fishing activities and methods used by populations in early fisheries and represent a first step towards the comprehension of pre-Columbian fishing strategies.

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